Review Article

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# A Review on Polymer Nanocomposites: Synthesis, Properties, and Applications

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**Abstract**

Polymer nanocomposite has been a rapidly expanding research topic for producing materials during the last few decades. Over the last two decades, there has been a significant scientific interest in nanoscience and nanotechnology. Nanomaterials' distinct features are related to quantum phenomena, greater surface area, and self-assembly. Quantum effects can begin to dominate matter's behaviour in the nanoscale, particularly at the lower end, affecting optical, electrical, and magnetic properties. Nanomaterials have evolved into nanocomposites with numerous applications. Its applications catapulted them to prominence in the field of material research. Because of their unique property combinations and design practicality, polymer nanocomposites are employed in sports equipment, wastewater treatment, the automobile industry, and biomedical applications. Even though they have numerous advantages, producing them in sufficient quantities and high quality is still one of the biggest challenges. During the last few decades, polymer nanocomposites have been a fast-developing research topic for material production. There has been a surge in scientific interest in nanoscience and nanotechnology during the last two decades. Nanomaterials have developed into nanocomposites, which have a wide range of uses. Its uses propelled them to the forefront of material research. Nanocomposites' physical, mechanical, barrier, flame retardancy, optical, dielectric, rheological, and thermal characteristics have been thoroughly researched. Their uses have also been discussed.

**Keywords:** Nanofiller, Graphene, Sensor, Hydrogel, Carbon Nanotube

## 1. Introduction

Nano Science and Nanotechnology is a multidisciplinary field that deals with materials and structures with dimensions as small as a billionth of a meter (nanometer).[1] Nanotechnology is a rapidly growing scientific field that involves tiny particles with a wide range of research applications, innovation, development, and industrial activities.

Polymer nanocomposites are multiphase hybrid materials with much improved thermal, mechanical, barrier, and flammability properties than the original polymer at low filler loading.[2] Polymer nanocomposites are finding a home in most of today's commodity items due to their capacity to provide increased features. Scientists' increased interest in nanocomposite materials is due to their much-improved qualities compared to a given pure polymeric material because a nanocomposite combines the properties of the polymer matrix with an inorganic substance. Thermal stability, crystallinity, and mechanical characteristics are a few examples. Because nanofillers have a high aspect ratio, a significant boost in polymer characteristics can be obtained at low nanofiller loadings. The process of increasing the properties of nanocomposites by incorporating constituents into the matrix material is known as reinforcing. Reinforcement, often known as nanomaterial, is a type of nano-filler material.[3]

Polymer nanocomposites provide an excellent opportunity to investigate new functions beyond traditional materials. One of the most exciting and developing study fields has been nanocomposites. They attract special attention due to their distinct lightweight, easy production, and flexibility

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## 2. Nanocomposites

There is a growing demand to alter the structure and composition of materials on nanometre scales worldwide. Polymer nanocomposites are polymers that have been mixed in minute amounts with nanosized filler particles (less than 10 percent). Polymer nanocomposites (PNCs) are a combination of two or more materials in which the matrix is a polymer and the dispersed phase has at least one dimension less than 100 nm. Incorporating modest concentrations of these nanofillers into polymers can increase their mechanical, thermal, barrier, and flammability qualities without altering their processability. Individual nanoparticles are homogeneously disseminated in a matrix polymer in the ideal design of a nanocomposite. The reinforcing impact of filler is ascribed to various aspects, including polymer matrix characteristics, the nature and type of nanofiller, polymer and filler concentration, particle aspect ratio, particle size, particle orientation, and particle dispersion. Nanocomposites have been discovered to have more beneficial properties than ordinary composite materials. Thus, understanding what occurs when nanocomposites of polymer and inorganic components are produced becomes crucial. Although particle-filled polymer composites have received extensive research due to their widespread use in the automotive, household, and electronic industries, nanocomposites have recently sparked scientists' interest worldwide due to their potential applications in high-performance coatings, electronics, magnetic, and biomedical materials. These nanocomposites are a novel type of matrix containing nanosized fillers. [4] Dimensionality is an essential factor in determining the properties of matter. The material nanostructure determines the novel properties of the structure. Nanotechnology is an interdisciplinary field. It merges several branches of science to generate materials with new properties.[5] The capabilities of polymer nanocomposites are accomplished by their extremely high aspect ratio, physical and chemical characteristics, and unique synthetic achievability. The nanoscale size of polymer nanocomposites allows them to confer physiochemical exchanges by changing the surface properties.

Polymers are categorized into two types: thermosetting polymers and thermoplastic polymers. The ability of thermosetting polymers to be reused is lost due to chemical changes. However, thermoplastic polymers can be treated when implanted with ordered orientated crystalline domains that are not chemically cross-linked. Polystyrene and PMMA are thermoplastic polymers that are transparent, lightweight, flexible, durable, and sturdy.[6] Thermoplastics are recyclable, metal-adhesive, corrosion-resistant, abrasion-resistant, impact-resistant, and electrically insulating. However, when reheated, it softens and is more expensive than thermosets. On the other hand, Thermoset's resist deformation is mechanically stiff and rigid, cost-effective, and produces more robust, more permanent chemical bonds. Carbon and its derivatives can be employed as reinforced materials due to their exceptional mechanical, thermal, optoelectronic, and electrical capabilities.[7]

## 3. Synthesis Of Nanocomposites:

3.1 **Solution Casting**: In solution casting, a polymer, a solution, and nano reinforcement are combined and thoroughly mixed by ultra-sonification the solution is allowed to evaporate. The solution leaves the nanocomposite as it gets evaporated. The nanocomposite thus obtained is in the form of a thin film. The solvent/solution selected should thoroughly dissolve the polymer while dispersing the nano reinforcement. The benefits of the resultant film include improved film thickness homogeneity and a more extensive range of film thicknesses ranging from 150 microns to less than 12 microns. Films that are free of gel and pinholes. Outstanding flatness and dimensionless stability. Because the film is not stretched during manufacturing, it has an isotropic orientation. There is no usual extrusion process lubricants present. The stability of polymer solution casting is tested on an individual basis based on the product application.[8]

The inclusion of additives and fillers has been simplified with a wide range of material options from either aqueous or solvent-based solutions. Acrylic and other polymer films have exceptional optical characteristics and consistent thickness. Polyurethane film improves mechanical properties by eliminating pinholes or cavities and ensuring film uniformity, excellent optical clarity, and the manufacture of thin films that can be easily customized with additional functional layers and properties. Where melt extrusion is not possible, Thermoset adhesive films are used. Thermal interface materials allow for the insertion of more concentrated thermally conductive fillers than the melt extrusion method allows. Electroactive polymer films give better optical characteristics, homogeneity, and gel and pinhole-free materials that do not allow high voltage breakdown failure.[9]

**3.2 Melt Bending:** There are various advantages to melt blending versus solution casting. When compared to solution casting, melt blending produced better gas barrier characteristics. Melt blending produced exfoliated nanocomposite structures, whereas solution casting produced intercalated structures. Melt blending has stronger creep resistance than intercalated blending. As an easy and ecologically safe approach, melt blending can be used to make nanocomposite films with exceptional physical properties.[10]

3.3 **Sol-Gel Process:** This is accomplished by two methods: hydrolysis of the metal alkoxides and then polycondensation of the hydrolyzed intermediates. Polymerization rate and tensions in metal alkoxides can also be controlled by employing chemically controlled condensation, in which the removal of water is delayed using esterification processes.

3.4 **In-situ Polymerisation:** In situ polymerization has several advantages. Thermoplastic and thermoset-based nanocomposites may be made using this method. [11]Furthermore, it allows for the grafting of polymers onto the surface of the filler, which can typically improve the characteristics of the final composite. This method allows partly exfoliated structures to prepare due to the excellent dispersion and intercalation of fillers in the polymer matrix.[12] Toyota researchers presented an in-situ intercalation method to produce polyamide nanocomposites, resulting in an exponential growth in nanocomposites research. The layered silicate mineral is swelled in a monomer to generate polymer nanocomposites using this approach. The polymerization of the monomer begins after swelling. As a result of the presence of monomers in and out of the filler interlayers, the produced structure is exfoliated or highly intercalated.[13]

3.5 **Electro-spinning:** Electrospinning is a valuable technology for producing polymeric nanofibers. Carbon nanotubes, graphene, and fullerenes and their derivatives, such as quantum dots, nanofibers, and nanoribbons, have gained attention. They provide unique structures and excellent physicochemical capabilities. The integration of nanocarbons in electrospun polymeric fibers has been used to improve the properties of polymer nanocomposite.[14]

## 4. Properties of Nanocomposites

4.1 **Mechanical properties:** The integration of nanoceramics into polymers, organized on a nanoscale scale with a high aspect ratio and a large surface area, improves their mechanical characteristics significantly. Many inorganic filers of micrometer dimensions, including calcium, carbonate, glass beads, and talc, have been utilized widely in traditional polymer composites to improve the mechanical characteristics of polymers. Such qualities may be customized by varying the volume percentage, shape, and size of the filler particles.[15]Using filler materials with a higher aspect ratio, such as short glass fibers, can increase mechanical qualities even more. Layered silicates and carbon nanotubes are examples of these fillers. Carbon nanotubes (CNTs) have a significantly higher aspect ratio (1000) than stacked silicates (200). Furthermore, flexible CNTs have a very high strain to failure.[16].Rigid inorganic nanoparticles with a lower aspect ratio can also reinforce and toughen materials in polymers. Nanofillers disperse poorly in polymers because of their incompatibility with polymers and high surface-to-volume ratio. Organic surfactant and compatibilizer additives are required to increase the dispersion of these nanofillers in polymeric matrices.[17]

4.2 **Barrier properties:** The barrier characteristics of polymer nanocomposites may considerably improve when they are supplemented with silicate clay, graphene and graphene oxide, boron nitride, and molybdenum disulfide. A significant reduction in the permeability and diffusivity of penetrant molecules opens the door to new applications for polymer nanocomposites in perishable food, pharmaceutical, and electrical device packaging materials, gas barrier membranes, water desalination and purification membranes, anti-corrosion coatings, and spacecraft in low-Earth orbit missions**.**[18]

4.3 **Flame retardancy:** Many materials deteriorate mechanical qualities while boosting flammability resistance. For quite some time, no substantial flame retardant technology has emerged in this field.[19] Polymer-clay nanocomposites have sparked much attention, owing to their increased mechanical and thermal properties. The formation of tortuous passways to obstruct the growth of flammable, volatile pyrolysis species is mainly employed to increase fire retardancy in layered silicate/polymer nanocomposites. In general, flame retardants increase flammability while decreasing polymer mechanical characteristics. However, it was discovered that polymer clay nanocomposites lowered polymer flammability while improving mechanical qualities. Thus, the major drawback in producing clay/polymer nanocomposites for fire retardancy is that improving structural efficiency for flame retardancy may result in poor mechanical properties..[20]

4.4 **Optical properties:** Polymer Nanocomposite materials have received much attention because of their intriguing optical properties that differ from those of individual metals. Combining metal with polymer improves the optical properties of nanometals while also changing the mechanical properties of the polymer.[21] Semiconductor and metallic nanoparticles and nanocomposites have unique linear absorption, photoluminescence emission, and nonlinear optical characteristics. Nanomaterials with small particle sizes display enhanced optical emission. Recently, much attention has been paid to preparing polymer semiconductors and other nanocomposite materials with potential applications in various optoelectronics and photonics devices.[22]

4.5 **Dielectric properties:** Dielectric spectroscopy (DEA) effectively investigates relaxation phenomena in polymers and composites. Dielectric studies in polyurethane-nano silica composites revealed that both the non-filled and filled composites exhibit an overlapping transition composed of two sub relaxations that get resolved only at the highest frequencies.[23] Wei *et al.* investigated the influence of poling on the dielectric characteristics of PT/PEK-C. Plasticization should be considered when determining the poling temperature of nanocomposite thin films. Furthermore, the viscosity of the polymer decreases and the alignment of Pt ultrafine particles is simple at high temperatures. However, the conductivity of PT/PEK-C composite thin films increases rapidly with temperature, indicating that the thin films are easily broken down at high temperatures.[24]

4.6 **Rheological properties:** Wang et al. reviewed the literature on nanofluid rheology and discovered that Brownian motion and nanoparticle aggregation play critical roles in the rheological properties of nanofluids. The viscosity of a liquid suspension is the measure of resistance provided by nearby layers to one another during the flow of the liquid suspension.[25]

For practical applications, we require materials with various characteristics and owing to the synergistic effect, hybrid nanofluids are projected to have greater thermal conductivity than individual nanofluids. Because of the unique features of carbon nanotubes, researchers are trying to build a new class of hybrid nanomaterials composed of a composite of carbon nanotubes and metallic, semi-conductive, or non-conductive nanoparticles.[26]

4.7 **Thermal properties:** The inclusion of nanoparticles into a polymer matrix modifies the polymer's mechanical, thermal, and other properties. The most common approach for creating such polymer composites is to disperse nanoparticles in a melted polymer or dissolve them in a solvent polymer. The nanoparticles are typically capped with organic molecules to achieve the required solubility in the appropriate solvent.[27]

Carbon nanoparticles are frequently used to improve the characteristics of polymer nanocomposites. Carbon nanofillers such as carbon nanotubes (CNT), graphene, fullerene, and carbon nanofibers (CNF) can modify the thermal stability of the polymer matrix through several processes that act between the carbonaceous fillers and the fundamental polymer matrix. Carbon nanoparticles can also affect glass transition temperatures, crystallization temperatures, and polymer phase crystallinity.[28]

## 5. Applications of Nanocomposites:

Polymer nanocomposites have distinct structures, morphological, mechanical, thermal, and electrical characteristics. As a result, research on polymer nanocomposites has been ongoing for almost 25 years. The shift from micro to nanoparticles causes changes in both physical and chemical characteristics.[29] Carbonaceous nanofillers such as graphene and carbon nanotubes (CNTs) hold great promise due to their superior structural and functional qualities such as high aspect ratio, high mechanical strength, high electrical properties, and so on.[30] Graphene or hybrid filler-based polymer nanocomposite-based electrochemical applications, lithium-ion batteries, sensors, solar cells, water purification, supercapacitor, drug delivery, and tissue engineering have all been successfully implemented by multiple studies**.** Nanotechnology can generate a plethora of novel materials and gadgets with several uses, including medical, electronics, and energy generation.[31]

5.1 **Polymer Nanocomposites for Food Packaging:** Packaging plays a vital role in keeping food safe and nutritious, but it can also cause problems due to their non-biodegradability, leading to environmental pollution and weak barrier properties water vapor and gases to maintain optimal quality of the food product. However, the manufacturing of nanocomposite for the application in food packaging is minimal due to the high manufacturing cost and lack of mass production feasibility.[32] The packing material's resistance to gas invasions such as oxygen and water vapor, as well as the retention of gases such as CO2 and smell, are significant limiting variables for the shelf life of many foods and drinks. CO2 migration from carbonated beverage bottles may reduce shelf life by flattening the contents. Polymer nanocomposites with various nanofillers have been created for better gas and water vapor barrier characteristics. [33]

The biodegradable clay polymer nanocomposite is an alternative material for packaging as nano reinforcement has gained active interest in the food sector. [34]According to the comparative study based on the life cycle assessment and cost, reducing the nano clay cost production weight could make the polymer nanocomposite competitive with conventional food packaging intending to scale up biodegradable clay polymer nanocomposites as an effective food packaging material.[35]

5.2 **Polymer Nanocomposites as chemiresistive sensors:** A chemiresistor is a substance whose electrical resistance fluctuates in reaction to changes in its surroundings. Chemiresistors are chemical sensors based on the direct chemical interaction of the sensing material and the analyte.[36] Many disadvantages of organic materials (polymers), such as low conductivity and poor stability, and inorganic materials, such as the necessity for high-temperature operation and advanced processability, prevent them from being used in gas sensor manufacturing.[37] To address these limitations, polymers can be functionalized or integrated with nanoparticles and carbon compounds, resulting in better gas sensing properties. The nanocomposites have demonstrated tremendous promise for application as chemical sensors, with significant increase sensitivity, strong repeatability, recovery, and great stability.[38]

5.3 **Biodegradable polymer nanocomposites for ligament/tendon tissue engineering:** The use of biodegradable polymer matrix to make nanocomposites offers numerous advantages, including the ability to adjust mechanical characteristics and degradation kinetics to suit a variety of applications. Adopting biodegradable matrices include their capacity to fully replace tendon or ligament tissues with a simple surgical approach, minimum patient morbidity and danger of infection or disease transmission, and speedy recovery to preinjury functionality by using biodegradable biomaterials.[39]

5.4 **Nanocomposites based on aerospace applications**: Graphene has outstanding mechanical properties, and molecular dynamics simulations show that it improves strength stability and reduces fatigue stress.[40] It displays extraordinary characteristics that can alter the aerospace industry. In the field of aircraft technology, nanocomposites have witnessed a remarkable increase, with high-end applications needing the usage of highly structural materials, which nanocomposites look to fulfill well. The usage of these materials has dramatically boosted the structural capabilities of specific components while also satisfying the aerospace industry's material and production standards.[41]

5.5 **Fuel cell using a polymer electrolyte membrane:** Polymer nanocomposite also applies in fuel cells. It is an effective method for improving the performance of typical proton conducting membranes such as Nafion, sulfonated poly(ether ether ketone) (SPEEK), to build a polymer nanocomposite by adding a nanofiller. A polymer nanocomposite membrane combines organic polymer qualities with inorganic filler, thus resulting in high proton conductivity

## 6. Future Prospect

The pace of innovative discoveries in nanotechnology is projected to pick up in the coming decade around the world. Nanocomposites will significantly impact existing and upcoming technologies in practically every industry sector, including material and energy conservation, biomedicine, and environmental sustainability. Nanotechnology advancements and ongoing research promise the production of additional possible nanocomposites with a wide range of practical applications. Nanocomposites typically have multifunctional qualities like high mechanical strength, high electrical conductivity, and increased optical properties, having a high surface-to-volume ratio for biomolecule loading.

According to experts, the worldwide nano market will be driven by increased usage of nanocomposites, notably in packaging, aerospace, energy, automotive, electronics, and many others. Manufacturers and Industries will use this technology to strengthen the stability and durability of their products through the supply chain to higher quality. The benefits of nanocomposites significantly outweigh the costs and limitations, and the technology will be enhanced and techniques created over time. Other nanofillers are being researched, enabling novel nanocomposite structures with superior characteristics to further nanocomposite utilization in various areas.[43] Depending on the complexity of the steps to be taken, the chosen technique might significantly impact nanocomposite quality.

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